Torsional Resonance Mode Imaging for High-Speed Atomic Force Microscopy

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Abstract. The instrumentation of high-speed imaging has been a challenge for scanning probe-based technologies. Mechanical stability of the system, surface tracking at sharp topographic transitions and prolonging tip lifetime have been the determining factors for practical applications. In this paper we report a new type of feedback control based on the torsional resonance amplitude (TRmode™) of cantilever probes. Atomic Force Microscope (AFM) dynamics are improved over TappingMode™ due to the much faster response of the TR amplitude signal when the tip is interacting with a surface. For a given cantilever, the amplitude error generation rate due to the topographic variation of surfaces is substantially higher in torsional resonance mode compared to that while tapping, leading to improvement in feedback loop response. We have demonstrated that the improved dynamics of the new TR imaging mode achieve much better surface tracking during high speed scanning across sharp steps. When torsional resonance amplitude is used in a nested feedback loop applying micro-actuated ZnO levers, the tracking error at 200 nanometer step edges can be controlled within 3 nm for a scanning speed around one millimeter per second. The tip/surface interaction of TRmode and TappingMode were studied in controlled experiments. In addition, we found that tip wear under torsional amplitude feedback control is comparable to that in low force TappingMode operation.

INTRODUCTION

Considerable effort has been applied to improving the performance of the atomic force microscope. Several groups have addressed increasing scanning speed in both air and fluid [1-6]. In TappingMode atomic force microscopy, there are three major factors limiting the increase of scanning speed: feedback loop electronics, cantilever dynamics and actuator bandwidth in three directions, especially along the vertical, Z-axis (perpendicular to the sample stage surface). For solving the problems associated with these limitations, researchers have adopted different approaches. Sulchek et al. used a micro-actuated cantilever to improve the Z-axis bandwidth by pushing up the resonant frequency 40 times higher than that of a regular piezo tube scanner [3]. With a nested feedback loop configuration, the microscope was operated with dual actuation for high-speed imaging. To deal with the slow response time of the tapping cantilever, Sulchek et al. implemented a circuit to actively

CP696, *Scanning Tunneling Microscopy/Spectroscopy and Related Techniques: 12th International Conf.*,
edited by P. M. Koenraad and M. Kemerink

control the Q value of the cantilever [5]. They scanned a grating sample at 5 Hz and demonstrated improved tracking of its step structure. However, the effect of Q-control can be achieved by imaging in TappingMode at a low setpoint. It is still under debate if it can fundamentally improve cantilever dynamics.

For the purpose of imaging biological samples in fluid, Ando et al. used customized feedback electronics and Z- and X-actuators to improve the bandwidth of the whole microscope. They also enhanced cantilever dynamics performance in water by using small cantilevers [6]. They achieved a tip velocity of 0.6 mm/s at a scan rate of 1.25 kHz.

While in TappingMode tip/sample interactions are mainly controlled in the vertical direction, other techniques have been developed which involve using the torsional properties of cantilevers for sensing tip/sample lateral interactions. There are numerous studies on tip/sample lateral interactions, shear forces, friction and nanotribology using related AFM technology [7-19]. The majority of the associated experiments used cantilever deflection as the feedback loop signal and detected the modulated torsional signal of the cantilever. Pfeiffer et al. used tunneling current under Ultra High Vacuum (UHV) conditions as the feedback control signal and detected the frequency shift of a cantilever oscillated at its torsional resonant frequency [18]. In Near Field Scanning Optical Microscopy (NSOM) and shear force microscopy the lateral amplitude of an optical fiber or a cylindrical cantilever perpendicular to the sample surface is used to control the distance between the probe and the surface [9].

We have developed a new imaging mode that uses cantilever torsional resonance amplitude as the feedback signal. Cantilever response is faster in TRmode than in TappingMode. In our experiments the same cantilever that performs the TappingMode imaging can be used in TRmode to scan the exact same area of the sample, allowing a direct comparison between the two modes. In addition we use micro-actuated ZnO cantilevers and nested feedback electronics for broadening the bandwidth of Z-actuation and of the feedback loop. To provide quantitative results, we systematically studied the error signals associated with the tip crossing a steep step. The enhanced performance of TRmode provides either smaller error amplitude at the same scan speed for improved accuracy or an increased scan rate with the same amount of feedback error as in TappingMode.

EXPERIMENTAL

The experiments were performed with a modified MultiMode AFM and a Nanoscope IV (NSIV) Controller system (Veeco Instruments Inc., Santa Barbara, CA). The modifications included switching, while the tip was retracted several hundred nanometers from the sample, between the vertical and lateral signals from a photodetector as the input signal to the feedback loop. In this way, the same area of the sample surface can be studied with both TappingMode and TRmode. We used a zinc oxide (ZnO) piezoelectric actuator to drive both the attached cantilever at its flexural and torsional resonant frequencies and for probe translation along the Z-axis (Nanodevices, CA). The details of the ZnO cantilevers have been described previously [4]. The flexural and torsional cantilever resonant frequencies were 189 kHz (Q=270) and 1267 kHz (Q=510), respectively. The sample we used is a grating with 10 μm pitch and 200 nm depth (Nanodevices, CA).

The schematic shown in Figure 1 depicts the nested feedback loop configuration of the NSIV Controller. Cantilever deflection is measured by a photodetector. The error signal is defined as the difference between the Root Mean Square (RMS) amplitude of the cantilever oscillation and a pre-determined setpoint value. The error signal is then fed into a high-speed analog feedback loop that outputs a voltage (within range ±14V) to the ZnO-actuated cantilever for controlling the separation between tip and sample. The output voltage from the fast feedback loop is connected to the input of the conventional digital feedback loop whose output voltage (within range ±220V) is used to drive the Z-piezoactuator in the scanner.

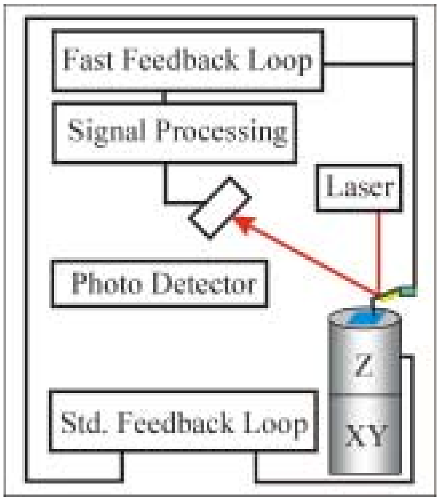


Figure 1.

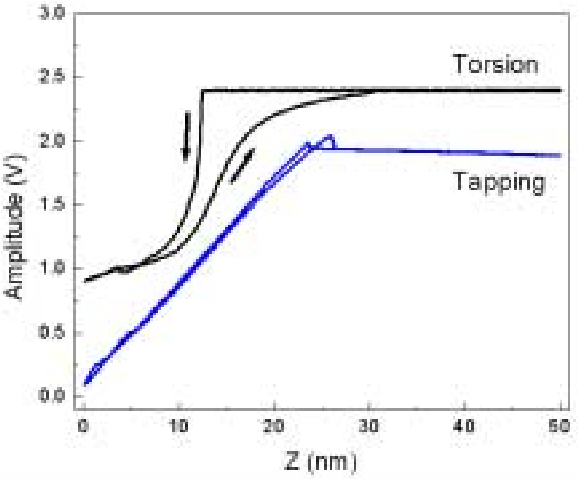


Figure 2.

Figure 1. Schematic of the nested feedback loop circuit in the NSIV Controller for using both a micro-actuated ZnO cantilever and the microscope Z-piezo as Z-actuators.

Figure 2. The amplitude vs. Z-position curves obtained with the cantilever in tapping and torsional modes. In TappingMode the cantilever oscillates at the resonant frequency of 189 kHz and the sensitivity equals 12.4 nm/V. In TRmode, the cantilever is driven at 1267 kHz and the sensitivity ranges from 1.1 to 4.5 nm/V.

There are three different imaging modes. The first mode uses the ZnO actuator to provide Z-motion only by setting the minimum gains in the digital feedback loop which controls the Z-piezo. The advantage of this mode is in enjoying the full benefit of the fast actuation of the ZnO lever, which has a resonant frequency of about 50 kHz. The disadvantage of this first mode is a total Z-range of only 700 nm. The second mode uses the ZnO lever and the Z-piezo of the tube scanner together for a larger Z-range and some improvement of the scanning speed. The disadvantage of this mode is overshoot of the Z-piezo with increasing speed. In the third mode, the analog feedback loop is disabled and the ZnO lever is used as a conventional tapping lever without contributing to Z-actuation. This mode is usually used for comparative studies and for taking “force curves” (cantilever oscillation RMS amplitude change as a function of tip/sample separation). In our experiments we used the first mode for its fast actuation capability and the third mode for collecting force curves. In this way we focused our study on differences in cantilever dynamic response.

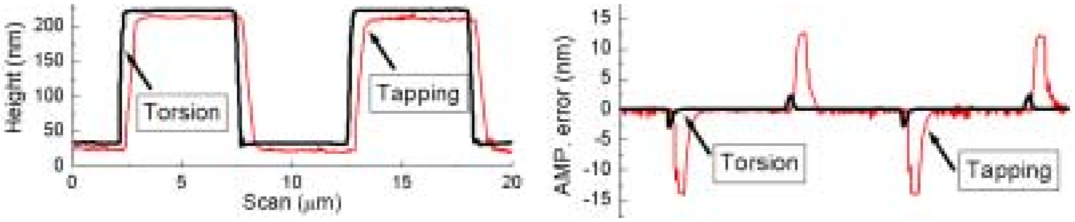
RESULTS

We collected force curves to understand cantilever dynamics in TappingMode and TRmode. For these experiments, feedback was turned off. The cantilever was driven by an AC voltage to oscillate at either the tapping (189 kHz) or torsion (1267 kHz) resonant frequency. The Z-piezo was then used to move the cantilever toward the sample until a cantilever oscillation amplitude drop was seen. The Z-piezo was then retracted to let the cantilever oscillation fully recover. The Z-piezo was cycled over a 50 nm range at a scan rate of 2 Hz. The two sets of force curves are plotted in Figure 2. Clearly, the approach portion of the force curve in TRmode has a much steeper slope than the analogous part of the TappingMode curve. We found that the slope of the torsion curve is between 1.1 and 4.5 nm/V, while the slope of the tapping curve is about 12.4 nm/V. In other words, to generate an error signal of 1 V, the cantilever needs to move 12 nm in the Z-direction in TappingMode, but only 1 nm in TRmode if operated at the steepest slope of the respective force curves. The steeper slope of TRmode is due to different interaction mechanisms between tip and surface.

At present we cannot fully explain the force curve behavior in TRmode. Similar force curves were observed in shear force microscopy studies on different samples [20, 21]. Antognozzi et al. reported a sudden drop in lateral oscillation amplitude of a cylindrical cantilever in Transverse Dynamics AFM, which they concluded was due to compressed water layers between the tip and sample exhibiting solid-like properties [22]. James et al. observed similar force curve shape contrast between hydrophilic and hydrophobic samples under different humidity conditions [23]. Also, we observed hysteresis between the approaching and retracting portions of the force curves, most likely due to capillary forces.

Consider the situation of a probe scanning over a surface step. Due to the topography change, the Z-piezo must move the tip up or down to maintain a constant tip/sample distance. If the feedback loop does not run perfectly, there will be an error signal, that is, the change in tip/sample distance introduced upon crossing the step edge. The amplitude and duration of this error signal are a function of the feedback loop gain settings and the scanning speed. Note that it is not valid to claim an increased scanning speed without proving that the error signal has not increased correspondingly. Also, use of high integral and proportional gains can reduce the error signal, but it increases the noise level in the feedback loop and in the height data. Therefore, only after comparing the error signal and the noise level at different scan rates can a scanning speed improvement factor be stated unambiguously. For the same error signal level in the feedback loop while traversing a step, we found that in TappingMode the height error can be as high as an order of magnitude larger than in TRmode.

In addition, as discussed by T. Sulchek et al. and other researchers previously, when the cantilever is scanning over a downward step in high-setpoint tapping, it takes time $\tau \sim Q/\pi f_0$ for the oscillation amplitude to grow, generating an error signal which induces the feedback loop to respond. This is usually the limiting factor for TappingMode scanning speed. In our situation the time constant in TappingMode is calculated as 0.46 ms, while in TRmode this time constant is about 0.13 ms, indicative of faster cantilever dynamics. Therefore, this is another reason for TRmode being able to support faster scanning than TappingMode.



(a)

(b)

Figure 3. Comparison of TappingMode and TRmode when imaging a grating surface with 200 nm steps. The image section lines plotted are a) height data, and b) amplitude error data. Scan size was 20 µm. Scan rate was 15 Hz. The same micro-actuated ZnO cantilever was used for Z-actuation in both modes.

Using the first operating mode with an integral gain setting of 0.0001 and a proportional gain of 0 in the digital feedback tube scanner loop, we scanned the grating sample in both TappingMode and TRmode with only the ZnO lever providing Z-actuation. The ZnO cantilever was previously calibrated with a height standard to have a sensitivity of 32 nm/V. This value was stored for automated conversion of FastZ data into nanometers. The line-scan FastZ (height) and FastRMS (error) data are shown in Figures 3a and 3b, respectively. At the scan rate of 15 Hz, or tip velocity of 0.58 mm/s, we observe that in TRmode the tip tracks the surface much better than in TappingMode. In the error signal data we found evidence of error signal saturation in TappingMode: the width of the peak is 2.5 times larger in TappingMode than in TRmode. Although the error amplitude in voltage looks similar in both modes (approximately 2.2 V in tapping and 1.8 V in torsion peak-to-peak values), the corresponding change in tip/sample distance differs dramatically. Converted to distance, the error in TappingMode is approximately 13.6 nm at the 200 nm step edge, in contrast to a 2.7 nm error in TRmode. (We used the average force curve slope of 3 nm/V in TRmode).

As mentioned earlier, high gains in the feedback loop reduce the error signal, but simultaneously increase the noise level. We observed that under our experimental conditions the noise level in both height and FastRMS for TappingMode are higher than for TRmode. From imaging data and roughness analysis, we conclude that the RMS noise level in TappingMode and TRmode error signals are 50 mV and 2.6 mV at this scan rate (15 Hz) , respectively.

To further compare the fast scanning performance of the two modes, we scanned the same area of the grating at different scan rates in both modes and acquired the series of images shown in the inset of Figure 4. The upper image in the inset is the height data in TRmode with a scan rate of 20 Hz, or 0.78 mm/s, and a scan size of 20 μm. The lower image is the torsion error signal collected simultaneously with the height data. From these images, we estimated the peak-to-peak values of the errors associated with traversing steps in both modes. Using the different conversion factors, 12.4 nm/V for tapping and 3 nm/V for torsion, we plot the data as a function of scan rate. We first performed TRmode scanning, followed by scanning in TappingMode. Then TRmode was exercised again to scan the same area at three different rates to check reproducibility.

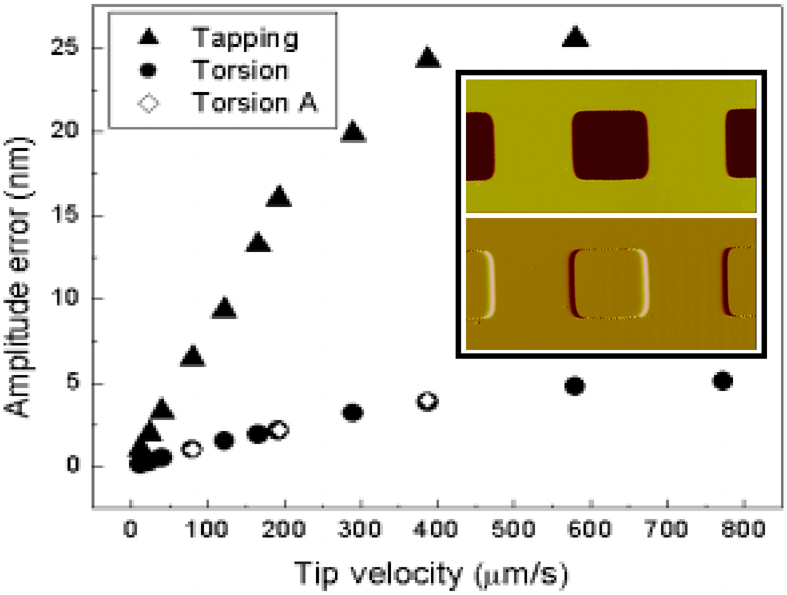


Figure 4. A series of images were obtained in both TappingMode and TRmode at different scan rates. The peak-to-peak amplitude error at the step edge was analyzed and plotted against scan speed. The "Torsion A" dataset was collected after finishing the comparison experiments; it checks for reproducibility and tip wear. The inset shows the height (upper) and error (lower) images in TRmode at 20 Hz. The scan size is 20 μm with a Z data scale of 350 nm in height and 6 nm in error signal.

We can divide the data into three regions based on scanning speed. In the first region the scan speed is slow, <50 μm/s, and the cantilever dynamics are fast enough for both modes at these speeds. Therefore, we see little difference between the two modes. In the second region, for scan speeds between 50 and 300 μm/s, we observed an almost perfect linear growth of the error signal with scan speed for both modes, though with different slopes. The TappingMode curve slope is about seven times larger than the TRmode slope, indicating that the feedback error data in TRmode at the step edge is about seven times smaller than in TappingMode at the same scan speed. For the same error amplitude, one can scan seven times faster in TRmode than in TappingMode. In the third region, the error signal no longer grows with scan speed in TappingMode. Looking at the shape of the error signal in the images (Figure 3b), we see that the peak width grows larger, while the amplitude change becomes less at high scan speed. This is a sign of the saturation of the integrator in the feedback loop. TappingMode height data obtained in this region shows step shape distortion.

CONCLUSIONS

It has been demonstrated that the faster cantilever dynamics in TRmode enables the high-speed imaging or better surface tracking. Furthermore, TRmode also minimizes tip wear and applied force during scanning that is an important factor for practical use of SPM imaging.

ACKNOWLEDGMENTS

The authors are indebted to Bob Daniels and Peter Neilson of Veeco Instruments Inc. for their technical assistance. We also appreciate the careful editing by Alan Rice, also of Veeco.

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